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Gain-Tunable Complementary Common-Source Amplifier based on a Flexible Hybrid Thin-Film Transistor Technology

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Abstract—In this letter, we report a flexible complementary common-source (CS) amplifier comprising one p-type spray-coated single walled carbon nanotube and one n-type sputtered InGaZnO₄ thin-film transistor (TFT). Bottom-gate TFTs were realized on a free-standing flexible polyimide foil using a maximum process temperature of 150 °C. The resulting CS amplifier operates at 10 V supply voltage and exhibits a gain bandwidth product of 60 kHz. Thanks to the use of a p-type TFT acting as a tunable current source load, the amplifier gain can be programmed from 3.5 V/V up to 27.2 V/V (28.7 dB). To the best of our knowledge, this is the highest gain ever obtained for a flexible single-stage CS amplifiers.

Index Terms—Flexible electronics, indium-gallium-zinc-oxide, carbon nanotubes, thin-film transistors, flexible thin-film circuits, complementary circuits.

I. INTRODUCTION

EMERGING new applications like wearable and textile integrated devices [1], soft electronic skins [2], and imperceptible implants [3] promise to revolutionize our daily life. To reduce manufacturing costs and at the same time enable entirely flexible systems, a wide range of electronic devices like sensors, batteries, and energy harvesters need to be integrated on the same foil. In order to realize this, high-performance and low-power flexible analog circuits performing tasks such as sensor signal amplification, or analog to digital signal conversion, are required.

Among state-of-the-art flexible electronic circuit technologies, metal oxide semiconductors, and in particular amorphous indium-gallium-zinc-oxide (IGZO), are especially attractive due to their high electron carrier mobility $>10\text{ cm}^2/\text{Vs}$ (in ambient air) and low temperature processability [4]. To date, flexible sputtered IGZO n-type thin-film transistors (TFTs) can be reliably integrated into complex, flexible and large area analog circuits [4]–[6]. Even if remarkable performance can be achieved with flexible unipolar IGZO analog circuitry, key requirements like low power consumption, high gain, and

simplified circuit design can only be accomplished by complementing n- and p-type TFTs [4]. Nevertheless, the realization of a flexible oxide-based complementary circuit technology suffers from the lack of a p-type semiconductor with matching performance and stability [4]. Therefore, there are only few reports on flexible circuits featuring n-type metal oxide TFTs n and p-type metal oxide [7]–[10] or organic [11]–[14] TFTs. Among these, only the work by Martins et al. shows analog amplifiers with p-type SnO TFTs acting as diode-load pull-ups [7]. This resulted in differential and common-source (CS) amplifiers with gains of 16.3 and 4.1 V/V, respectively. Recently, solution-processed single walled carbon nanotubes (SWCNTs) have emerged as an attractive material to complement IGZO in both digital and analog circuits [15]–[19]. In this context, Honda et al. demonstrated both inverting [17] and differential [19] amplifiers based on sputtered IGZO and dip-coated SWCNTs. While their inverting amplifier yields a DC gain of 1.8 V/V, their differential amplifier (3 IGZO TFTs and 2 SWCNT TFTs acting as diode-load) exhibits a gain of 38.5 V/V.

In this letter, we present a gain-tunable CS amplifier based on one n-type IGZO TFT and one p-type SWCNT TFTs which acts as a tunable current source load. The amplifiers exhibit a gain bandwidth product (GBWP) of 60 kHz at a supply voltage of 10 V. By adjusting the gate bias voltage of the SWCNT p-type TFT, the voltage gain of the amplifier can be tuned from 3.5 up to 27.2 V/V (28.7 dB). To the best of our knowledge, our amplifiers yield the highest gain ever reported for flexible single-stage CS amplifiers.

II. FABRICATION PROCESS AND DEVICE STRUCTURE

The flexible complementary amplifiers were manufactured on a free-standing 50 μm -thick polyimide foil (area: $7.6 \times 7.6\text{ cm}^2$), employing a 6-mask process and a maximum fabrication temperature of 150 °C. Fig. 1 shows: (a) the schematic cross-section and (b) a photograph of a fully processed flexible substrate. N-type IGZO TFTs employ an inverted staggered and passivated bottom-gate (BG) geometry, whereas p-type

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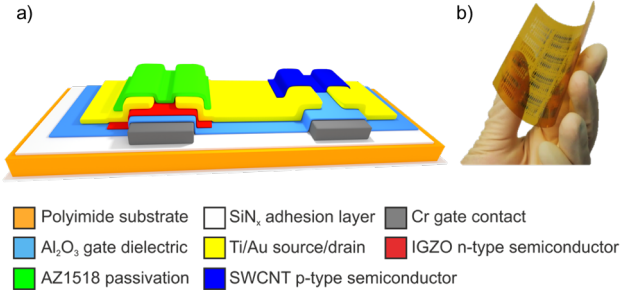


Fig. 1. (a) Schematic cross-section of complementary amplifier based on n-type IGZO and p-type SWCNT TFTs fabricated on a free-standing polyimide foil. (b) Photograph of an entirely processed flexible substrate.

SWCNT devices present a coplanar and unpassivated BG structure. First, the foil was first covered with 50 nm SiN_x adhesion layers and then coated with a 30 nm-thick Cr film which was subsequently structured into gate contacts (photomask 1) [5]. Next, 50 nm Al_2O_3 gate dielectric (dielectric constant of ≈ 7.5) was grown by atomic layer deposition (ALD) at 150 °C. Subsequently, a 15-nm thick IGZO film was RF magnetron sputtered at room temperature from an InGaZnO_4 target (in a 10 sccm Ar atmosphere at 10^{-6} mbar using 75 W RF power) from an InGaZnO_4 target. After patterning the semiconductor islands and the gate contact holes (masks 2 + 3) [5], 10 nm Ti and 50 nm Au source and drain (S/D) electrodes and interconnections were formed (mask 4) [5]. Successively, the IGZO was first passivated with AZ1518[®] photoresist (mask 5) [16], and subsequently complemented with solution-processed SWCNTs [20], acting as a p-type semiconductor. The as-received solution of 0.001wt% 99.9% semiconducting SWCNTs (NanoIntegris) dispersed in de-ionized (DI) water was spray coated at 50 °C through a shadow mask (mask 6). To allow the growth of uniform SWCNT films, a stack of 16 sprayed layers (total thickness: 3.7 nm post dispersant removal) was used. Finally, the dispersant was removed in a DI water post-deposition treatment. All TFTs have interdigitated channels with lengths of 10 μm .

SPICE simulations (level 61 model in HSPICE [5]) based on the characterization of single TFTs were used to design CS amplifiers robust to changes in the mobility of the devices. Fig 2 displays the circuit schematic (a) and diagram (b) of a complementary amplifier constituted by an n-type IGZO TFT ($W/L = 8400 \mu\text{m}/10 \mu\text{m}$) and a p-type SWCNT TFT ($W/L = 7200 \mu\text{m}/10 \mu\text{m}$).

III. RESULTS AND DISCUSSION

Single TFTs were characterized under ambient conditions using a semiconductor parameter analyzer (Agilent B1500A). The CS amplifier was measured under ambient atmosphere by applying a sinusoidal signal with peak-to-peak amplitude V_{IN} of 100 mV and offset $V_{\text{B,n}}$ to the gate of the n-type IGZO TFT. At the same time, the p-type SWCNT TFT was supplied with a bias voltage $V_{\text{B,p}}$ in order to act as a current source load. The resulting output signal was monitored with the aid of an

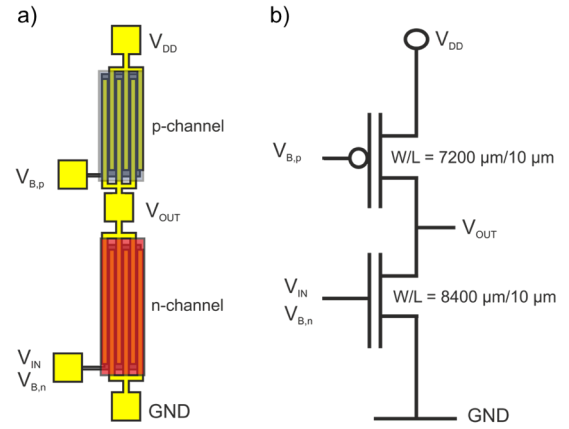


Fig. 2. Circuit schematic (a) and diagram (b) of a flexible current source load CS amplifier (all TFTs have $L = 10 \mu\text{m}$ and interdigitated channels). The sinusoidal signal is applied at the n-type IGZO TFT gate, whereas n- and p-type TFT are supplied with $V_{\text{B,n}}$ and $V_{\text{B,p}}$, respectively.

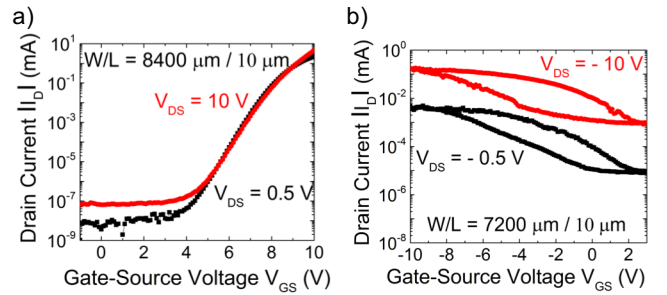


Fig. 3. Transfer characteristic of: (a) flexible n-type IGZO TFT and (b) p-type SWCNT TFT measured in air (channel length $L = 10 \mu\text{m}$ for both).

oscilloscope with a total resistive and capacitive load of 1 M Ω and 2 pF, connected to the amplifier output [21].

Fig. 3 (a) displays the transfer characteristics of a flexible n-type IGZO TFT. From the measurement data shown in Fig. 3 (a), a saturation field-effect electron mobility $\mu_{\text{FE,n}}$ of $18 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, a gate leakage current $|I_{\text{G}}| < 10 \text{ nA}$, a current on/off ratio $I_{\text{ON}}/I_{\text{OFF}}$ of 8×10^7 and a negligible clockwise hysteresis $< 25 \text{ mV}$ were extracted. A larger threshold voltage V_{TH} of 8 V is a result of the non-annealed IGZO film [16]. The SWCNT devices [Fig. 3 (b)] exhibit a clear p-type characteristic with a saturation field-effect hole mobility $\mu_{\text{FE,p}}$ of $0.1 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, a V_{TH} of -3 V, an $|I_{\text{G}}| < 10 \text{ nA}$, and an $I_{\text{ON}}/I_{\text{OFF}}$ of 180. The low on/off current ratio is mainly attributed to the not fully de-bundled SWCNT network. Even at high semiconducting content, a poor dispersion can lead to a metallic behavior in bundles if a metallic tube is present [22]. Nevertheless, the low on/off current ratio of the SWCNT TFT has no influence on the amplifier performance, as shown later in this letter. In comparison to our previous work on flexible complementary circuits with p-type SWCNT TFTs [16]–[18], our devices yield a reduced counter clockwise hysteresis $< 2 \text{ V}$ and an improved stability (shelf lifetime in air > 300 days). By passivating the SWCNT TFTs, we expect a further reduction of the hysteresis.

Fig. 4 shows the electrical characterization of the current source load CS amplifier. To find the optimal operating point of the amplifier, pairs of different bias voltages of both p- and

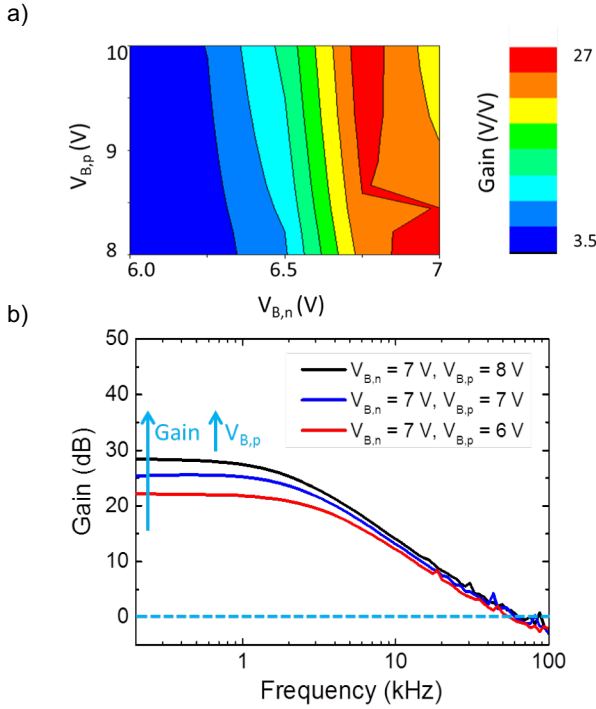


Fig. 4. Flexible complementary CS amplifier measured in ambient air: (a) voltage gain G as a function of the bias voltages $V_{B,n}$ and $V_{B,p}$. Optimal gain $G = 28.7$ dB is achieved at $V_{B,n} = 7$ V and $V_{B,p} = 8$ V ($f_{IN} = 100$ Hz). (b) Bode plot at different $V_{B,p}$. $f_c = 2.2$ kHz, showing the effect of different $V_{B,p}$ on the gain and bandwidth.

n-type TFTs ($V_{B,p}$ and $V_{B,n}$) were tested at a frequency of 100 Hz and the corresponding voltage gain (G) was measured (Fig. 4 (a)). The graph in Fig. 4 (a) illustrates how the gain can be modulated through $V_{B,p}$ and $V_{B,n}$ in order to reach a peak value $G = 28.7$ dB (at $V_{B,n}$ of 7 V and $V_{B,p}$ of 8 V). In particular, the DC gain changes with respect to $V_{B,p}$ with a gradient as high as 4.6, whereas the degree of change of the gain with $V_{B,n}$ is lower (3.8). To the best of our knowledge, this is the highest gain ever reported for flexible complementary single-stage amplifiers [7], [17]. Thanks to the use of p-type SWCNT TFT acting as current source load, this gain exceeds also the best value shown for flexible unipolar single-ended CS amplifiers [21], [23]. Furthermore, this is the first demonstration of a flexible complementary gain-tunable single-stage amplifier. The Bode plot of the circuit operated at different $V_{B,n}$ and $V_{B,p}$ measured in ambient air is shown Fig. 4 (b). At $V_{B,n} = 7$ V and $V_{B,p} = 8$ V, the CS amplifier yields a cutoff frequency f_c of 2.2 kHz and a gain bandwidth product GBWP of 60 kHz. Different values of $V_{B,p}$ result in lower gains but in the same GBWP of ≈ 60 kHz. To the best of our knowledge this is also the highest GBWP reported for flexible complementary amplifiers with n-type IGZO TFTs [7], [17], [19]. Further improvements of the GBWP can be accomplished by adopting shorter channel length and using a self-alignment process to reduce the overlap capacitance between gate and S/D contacts [23]. At the same time, greater DC gains can be achieved by increasing the supply voltage [24], but at the cost of higher power consumption.

Finally, to prove the mechanical bendability of our CS amplifiers, we attached them to a cylindrical rod of 1 cm radius

using double-side tape. Full circuit functionality with negligible variations ($<5\%$) in both DC gain and GBWP down to 0.3% tensile strain and even after re-flattening proves the suitability of our technology for mechanically flexible electronics system. The mechanical bendability of our CS amplifiers can be further increased by employing more strain-resistant materials (e.g. employing Cu gate contacts [25]) and/or by reducing the overall applied strain (e.g. by utilizing thinner substrates [26]).

IV. CONCLUSION

In this letter, we have demonstrated a flexible complementary CS amplifier employing one n-type IGZO TFT and p-type SWCNT TFT yielding a DC gain of up to 28.7 dB (at a supply voltage of 10 V). The combination of a n-type active TFT and a p-type TFT acting as a tunable current source load allowed tuning the DC gain from we were able to modulate the DC gain from 3.5 V/V to 27.2 V/V, by selecting the appropriate bias voltages for the n- and the p-type device. To the best of our knowledge, this is the first demonstration of a flexible programmable-gain single-stage amplifier. Regardless of the DC gain selected, the GBWP of our CS amplifiers is 60 kHz, which is also the highest value reported for flexible complementary amplifiers featuring n-type IGZO TFTs. Finally, our CS amplifiers are fully operational while bent to 1 cm radius and after subsequent re-flattening.

These findings are an important step towards the realization of large-scale, bendable, flexible electronic systems, which require high-performance sensor signal amplification. In particular, the gain programmability is especially important for signal conditioning and communication electronics.

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